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14. ABSTRACT
Report developed under SBIR contract for topic A12-069. This project aims at addressing and remedying the serious limitations of the three-decade old multibody system (MBS) software technology currently used in the analysis, design, virtual prototyping, and performance evaluation of modern vehicle systems. These limitations are well known and are documented in the literature. The analysis of modern vehicle systems requires the development of complex models that include significant details that cannot be captured or accurately simulated using existing MBS codes which are based on rigid body assumptions or small deformation finite element (FE) formulations that are not suited for efficient communications with CAD systems. It is the main objective of phase I of this SBIR project to demonstrate the feasibility of developing a new MBS software technology that is based on new concepts and algorithms that can be used for accurate and efficient simulation of military and civilian wheeled and tracked vehicle models that include significant details.

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Project Summary

This project aims at addressing and remedying the serious limitations of the three-decade old multibody system (MBS) software technology currently used in the analysis, design, virtual prototyping, and performance evaluation of modern vehicle systems. These limitations are well known and are documented in the literature. The analysis of modern vehicle systems requires the development of complex models that include significant details that cannot be captured or accurately simulated using existing MBS codes which are based on rigid body assumptions or small deformation finite element (FE) formulations that are not suited for efficient communications with CAD systems. It is the main objective of phase I of this SBIR project to demonstrate the feasibility of developing a new MBS software technology that is based on new concepts and algorithms that can be used for accurate and efficient simulation of military and civilian wheeled and tracked vehicle models that include significant details. The new software technology will allow for: 1) preserving CAD geometry when FE analysis meshes are created; 2) modeling large deformation in MBS applications; 3) implementation of general constitutive models; 4) development of new efficient FE/MBS meshes that have constant inertia and linear connectivity conditions; and 5) use of numerical integration procedures that satisfy the constraint equations at the position, velocity, and acceleration levels; these integration methods will not require the numerical differentiation of the forces, and will take advantage of the sparse matrix structure of the MBS dynamic equations. A successful integration of CAD computational geometry (CG), nonlinear large displacement FE, and flexible MBS algorithms is necessary for the development of the new software technology. Such an efficient integration can be accomplished using the nonlinear FE absolute nodal coordinate formulation (ANCF) that allows for preserving CAD geometry, implementing general material models, using general large deformation continuum mechanics approach, developing new FE meshes that have constant inertia matrix and linear connectivity conditions, and exploiting the sparse matrix structure of the MBS dynamic equations. Implicit and explicit numerical integration procedures that ensure that the constraint equations are satisfied at the position, velocity, and acceleration levels will be used in order to avoid violations of the basic mechanics principles.

Background

MBS computer codes are widely used in the analysis, design, and performance evaluation of many industrial and technological systems as the ones shown in Fig.1, Nonetheless, for the past three decades, there has been no implementation of significant new formulations in MBS computer codes. This is evident by the history of this field which shows that the last major formulation developments were introduced more than three decades ago. MBS-simulation programs used in the analysis of models that consist of rigid components were introduced in the middle seventies; while the integration of *small deformation* finite element (FE) and MBS algorithms was successfully accomplished approximately three decades ago (early eighties). As

pointed out in the SBIR Phase I proposal, this old MBS technology, which has been used extensively and has served well the industry, federal laboratories, and academic research, has capabilities and features that will remain as important options for modeling small deformations in MBS system applications. Nonetheless, this old software technology are based on algorithms that have structures and procedures that do not allow for the integration of geometry and analysis or for the systematic analysis of large deformation problems in MBS applications. Therefore, existing MBS software technology cannot be used to meet the new challenges of developing more detailed models in which the effects of significant changes in geometry and large deformations cannot be ignored. New applications require accurate continuum mechanics based vehicle/soil interaction models, belt and chain drive models, efficient and accurate continuum based tire models of cables used in rescue missions, models that accurately capture large deformations due to thermal and excessive loads, more accurate bio-mechanics models for ligaments, muscles, and soft tissues (LMST), etc. In order to be able to address the challenges of modeling modern complex systems, successful integration of CG/FE/MBS algorithms is necessary. Phase II of this project will the first step to successfully integrate CG/FE/MBS algorithms (Fig. 2). This will eventually allow the industry to perform flexible MBS simulations using only one software and one license instead of the three different commercial software that are currently being used; one is the CAD system for solid modeling, the second is an FE code for determining the data required for modeling flexible bodies, and the third is the MBS code.

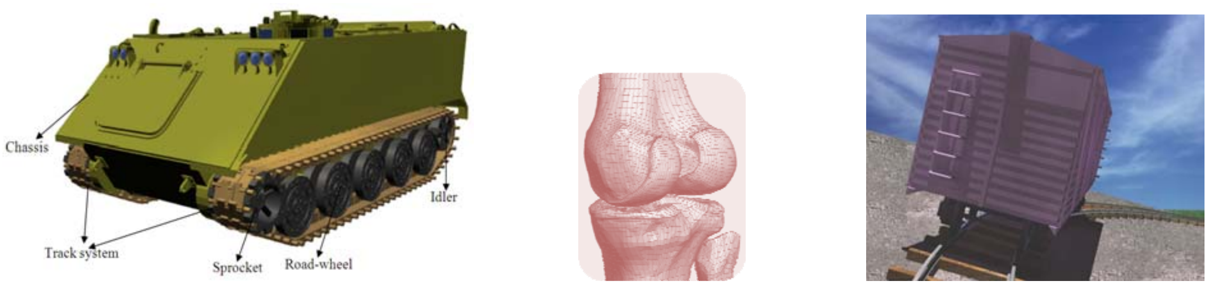

Figure 1 Examples of multibody systems

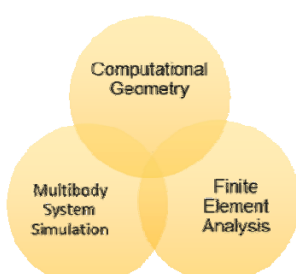

Figure 2 CG/FE/MBS integration

Project Objectives

The objectives of this project are summarized as follows:

1. **Integration of CG/FE/MBS Algorithms** The feasibility of integrating CG/FE/MBS algorithms using ANCF finite elements will be demonstrated in Phase I of this project. The limitations of using the isogeometric approach in MBS analysis will also be explained.

2. **Large Deformations and Material Models** The feasibility of developing general large deformation algorithms that have new features and can be the basis for the development of the new software technology will be demonstrated in this SBIR project.

3. **New Kinematic and Inertia Description** The feasibility of developing and using the FE meshes that have constant inertia and linear connectivity conditions and their implementation in a general MBS algorithm that can be used as the basis for developing the new software technology will be demonstrated in Phase I and Phase I Option of this project.

4. **New Numerical Solution Procedure** The principal investigator (PI) recently proposed an implicit sparse matrix integration procedure, called TLSMNI (**T**wo-**L**oop **S**parse **M**atrix **N**umerical **I**ntegration) that ensures that the kinematic constraint equations are satisfied at all levels, exploits the sparse matrix structure of the constrained dynamic equations, and avoids the numerical differentiation of the forces. The use of this new procedure will be examined and the feasibility of its implementation will be demonstrated in this SBIR project.

The objectives of this project have not been changed.

Results, Progress, and Accomplishments of Phase I

The progress and accomplishments of this SBIR Phase I project can be summarized as follows:

1. **New ANCF Meshes** A new flexible-link chain model was developed for tracked vehicle simulations. In this model, the links of the track chain shown in Fig.3 are modeled as flexible bodies connected by joints. This model demonstrated the feasibility of developing ANCF/MBS models with significant details that cannot be captured using existing MBS simulation tools. Significant improvement in computational efficiency has been achieved with this flexible-link chain tracked vehicle model. The flexible-link M113 model shown in Fig. 1 (a) can now be simulated on a PC in less than 4 hours. This could be achieved using ANCF finite elements that can be the basis for successful integration of CG/FE/MBS algorithms. As reported in the Interim Progress Reports, it was possible to achieve this significant improvement in the computational efficiency because ANCF finite elements lead to constant inertia matrix and linear connectivity conditions. This allows for the elimination of the large number of chain joint algebraic constraint equations at a preprocessing stage. By using ANCF finite elements to model the chain

joints, 720 nonlinear algebraic constraint equations were eliminated, and the number of non-zero entries was reduced by approximately 12000. The result is a significant reduction in the dimensions and the numbers of the non-zero entries of the sparse matrices used at the position, velocity, and acceleration levels. It was shown that when the stiffness of the track links is reduced, the flexible-link chain model can be simulated faster than the rigid-link chain model because of the unique features of the new ANCF FE meshes (Hamed et al., 2011; Shabana et al., 2012). The progress made in this area represents a significant step for the successful completion of the feasibility study of this project since it demonstrates that it is feasible to model efficiently flexible-link tracked vehicle models using the proposed MBS algorithms. CDI, UIC, and TARDEC are currently working on documenting the results of this study in a technical report that will be considered for journal and conference publications.

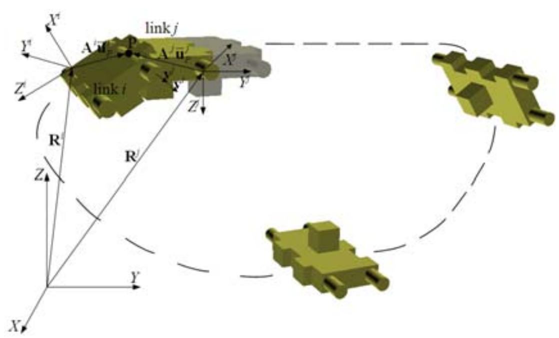

Figure 3 Links of the track Chain

2. **Joint Modeling and Validation** The feasibility of obtaining the joint forces for the ANCF flexible-link chain tracked vehicle model was demonstrated during Phase I of this project. The results of the ANCF model are compared with the joint force results obtained using the rigid body models. CDI and UIC performed extensive comparative numerical study to evaluate the accuracy of the ANCF joint modeling by comparing the results of the ANCF joint formulation with the results obtained using several rigid body formulations that include the ideal joint, the penalty, and the compliant joint models. The computer code developed by the PI and currently used by CDI and UIC allows for the systematic developments of all these models. Many of the subroutines in this code will be used in the new software computer program to be developed in Phase II of this project in order to accelerate the development of this new code. CDI and UIC have been working on documenting the results of this comparative numerical study in a paper, which will be presented at the ECCOMAS conference to be held this summer in Europe. This paper, which will also be considered for journal publication, has been updated to include results from the newest M113 tracked vehicle model, including ANCF joint model results. The results of the flexible-link chain model of the M113 vehicle are compared with the results of the rigid-link model (see for example Fig. 4). This paper was submitted to TARDEC

for the OPSEC approval. CDI also started working on the optimization of the rigid-link contact subroutines in order to reduce run times for both rigid and flexible models.

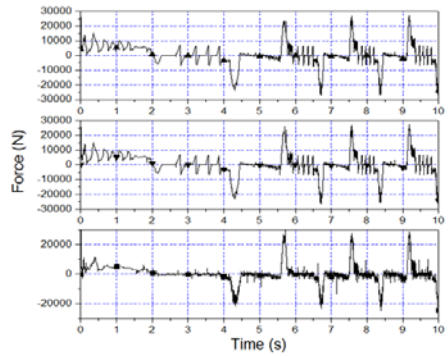

Figure 4a: Joint vertical forces
(—▲— Constrained joint model, —▼— Penalty method model k = 1×10^{9} N/m, —■— ANCF model)

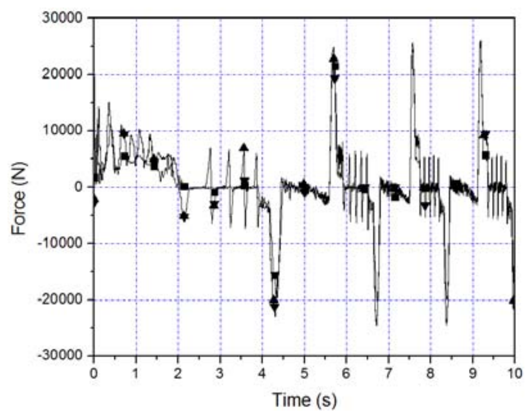

Figure 4b: Filtered joint vertical forces using FFT
(—▲— Constrained joint model, —▼— Penalty method model k = 1×10^{9} N/m, —■— ANCF model)

3. **Continuum-Based Soil Models** CDI demonstrated, using a simple example, the feasibility of the implementation of continuum-based soil models in MBS algorithms. CDI will continue to generalize and improve this implementation. The Cam-Clay model is being used as an example. The focus has been on developing a numerical model that demonstrates that general continuum-based soil models can be systematically integrated with ANCF/MBS algorithms. CDI and UIC are working on the developing of ANCF solid elements that will be used in the soil modeling. The results that will be obtained using the continuum-based soil models will be compared with the results obtained using the simpler terramechanics models. CDI, UIC, and TARDEC developed a comprehensive review paper which was accepted for publication in the Applied Mechanics Review. This

paper was revised to focus on the continuum soil models and their applications in terramechanics. An in-depth literature review has been performed on the use of finite element soil models in terramechanics applications. This literature review is being summarized and incorporated into the paper. The commentary provided by Dr. Jayakumar was addressed and incorporated into the third revision of the paper. The ANCF sections of this paper were significantly revised in order to describe clearly the integration of continuum-based soil models with ANCF/MBS algorithms. The revised paper was submitted for possible publication on Friday, February 1, 2013.

4. **CG/FE/MBS Integration** It is planned in Phase II of this project to start working on the important problem of the geometry/analysis integration. One of the important problems that must be addressed when using ANCF finite elements to describe complex geometry is the determination of the gradient vectors in the reference undeformed configurations. In order to develop, efficient and effective ANCF/MBS algorithms that can be used in the complex geometry cases of soil, tires, track links, fuel tanks, etc., the user must be able to easily define the gradient vectors in the reference configuration. CDI has implemented a new procedure in which the ANCF fully parameterized 3D beam elements are used to develop ANCF surfaces using parametric relationships defined using cubic splines (Mikkola and Shabana, 2012). Using the cubic spline functions, the gradient vectors of the ANCF plate elements can be determined. CDI and UIC are experimenting with the use of this new procedure by applying it to the modeling of the switches in railroad vehicle systems. This new procedure will allow for the definitions of new ANCF geometric surfaces that have different degrees of continuity. The development of such surfaces is necessary for the successful integration of computer aided design and analysis (I-CAD-A) since alternatives for the concepts of the knot vectors and knot multiplicity have to be found (Sanborn and Shabana, 2009; Lan and Shabana, 2010).

5. **Comprehensive FFR Implementation** As mentioned in the previous report, in addition to the ANCF implementation, future MBS computer programs will require having a floating frame of reference (FFR) formulation implementation in order to be able to efficiently solve small deformation problems. Currently, this implementation requires the use of commercial finite element codes as preprocessor to MBS computer codes. This requires the user to have two separate licenses; one for the FE code and the other for the MBS code. CDI and UIC continued the feasibility study to examine the possibility of developing a comprehensive FE preprocessor that can be integrated with the MBS computer code to be developed during Phase II of this project without the need for using another commercial FE code. As mentioned in the previous two interim progress reports, this feature will allow the user to perform a complete flexible MBS analysis using one code that can be acquired using one license only. CDI continued to work on this feasibility study to demonstrate that the code to be developed in Phase II of this project will allow developing large scale flexible body models that have different

element types. For example, one flexible body model may consist of plates, beams, solid, and shell elements as well as discrete springs. CDI is currently studying the use of an eigenvalue analysis solver that will require minimum storage. Having such an eigenvalue solver will allow for modeling large scale vehicle systems.

6. **Phase II Proposal Submission** CDI prepared and submitted the proposal for Phase II of this project. This proposal outlines the steps for developing the new MBS software technology.

Presentations and Meetings

1. The PI visited TARDEC on November 15, 2012 and made a presentation titled "Development of New Generation of Multibody System Computer Codes". In this presentation, the goals of this SBIR project were discussed.

2. The Start of Work Meeting was held during the PI's visit to TARDEC on November 15, 2012. The PI met with Dr. Jayakumar.

3. A teleconference was held on Wednesday, November 21, 2012. A presentation was made by UIC student Ulysses Contreras on the status of the soil mechanics modeling. The status of the subcontract to UIC was also discussed.

4. A teleconference was held on Tuesday, February 19, 2013. A presentation was made by CDI engineer Ulysses Contreras on the status of the soil mechanics modeling, and another presentation was made by UIC student Ashraf Hamed on the track vehicle model.

5. A teleconference was held on Thursday, March 21, 2013. During this teleconference, Ahmed Shabana made a presentation on the status of the SAMS/2000 code.

6. A teleconference was held on April 2, 2013. A presentation was made by CDI Engineer, Ulysses Contreras on the status of the soil model.

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